ACM e-Energy 2015 - Adapted

Rethinking Grids with Local Power Distribution

July 17, 2015

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First paper on IT energy use (1990)

ANNUAL REVIEW OF ENERGY
VOLUME 15, 1990

ELECTRICITY USE IN INFORMATION TECHNOLOGIES

Loadshape of IT remote usage based on data from IT equipment – to infer energy use

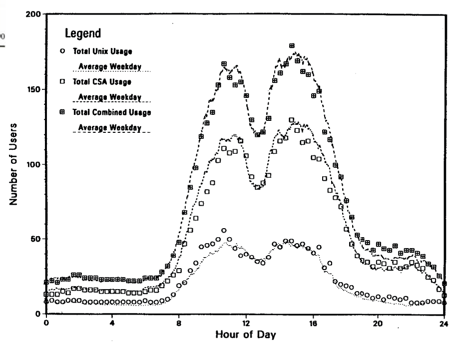


Image from Eric Brewer talk
"**Energy in the Developing World**"
January 14, 2010
(LoCal Retreat)

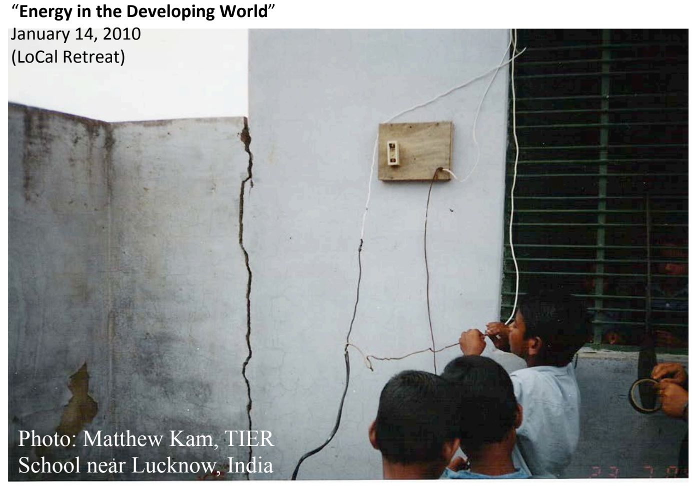
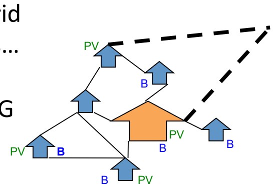


Photo: Matthew Kam, TIER
School near Lucknow, India

Community example

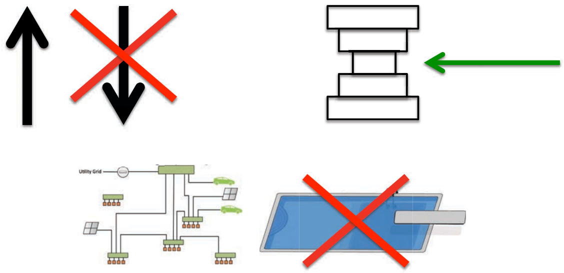
- Each building is its own nanogrid
  - Household, school, business…
  - Most will include storage
  - Many also generation; 2nd nG
- All buildings connected in a mesh
- Highly dynamic
  - Equipment additions and failure
  - Connections between buildings
  - Connections to utility grid – always, never, intermittent
- Operates simply and automatically
- Power flow changes direction



Features we should demand for power distribution

- "Plug-and-play" operation
  - End-use devices
  - Local generation
  - Local storage
- Arbitrary power topologies – inter-building links
- Improved safety
- Fine-grained management of constrained supply
- Greater efficiency with Direct DC
- Greater reliability – and lesser
- Universal technologies
- Enabling optimal operation with a local price
- Security / privacy

Key points



- Network model of power
- Network Power Integration
- Local Power Distribution
- Nanogrid

Unpacking "LPD"

- "Local" – within a building (or campus)
  - Not involving utility grid
- "Power Distribution"
  - "Technology / infrastructure that moves electrons from devices where they are available to devices where they are wanted"

Local Power Distribution is a
network model of power

Overview

- Technology paradigms
  - electricity and communications
- Need for a network model of power
- Network Power Integration
- Local Power Distribution (LPD) with Nanogrids
- Power quality and reliability
- Next steps

Telecom past

- My childhood home phone*

- Part of monolithic phone system
- Incapable of independent operation

One telecom future

- Digitize our 19th century system

- Slightly better version of old technology
- Still can't do anything really new

Promised telecom future

- Videophone - 1964 World's Fair (New York)

- Never happened
- Still point-to-point model

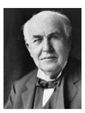
The telecom future we chose

- Multiple fundamentally new technologies and paradigms

- Does many things impossible with old concept
- Highly useful even with no ‘grid’ connection
- *Much more expensive than old telephony*

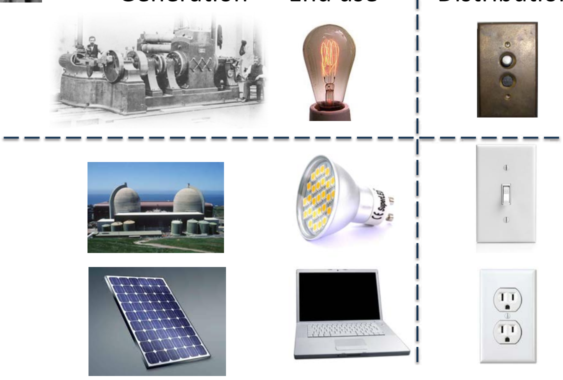
Grid terminology

- **Microgrid** Capability
  “… electricity distribution systems containing loads and distributed energy resources, (… generators, storage …, … loads) that can be operated in a controlled, coordinated way either while **connected to the main power network or while islanded**.” *(CIGRE C6-22)*
  US DOE defn. implies must be connected to utility grid
- **Nanogrid** Simplicity
  “A **single domain of power**; single voltage, frequency (if AC), reliability, quality, capacity (power), **price**, and administration. Storage is internal to a nanogrid.” Generation forms its own nanogrid. *(Nordman, 2010)*
- **Picogrid** Singularity
  An **individual device with its own internal battery** for operation when external sources are not available or not preferred, and managed use of the battery. *(S. Ghai et al. in* e-energy 2013; *paraphrased)*



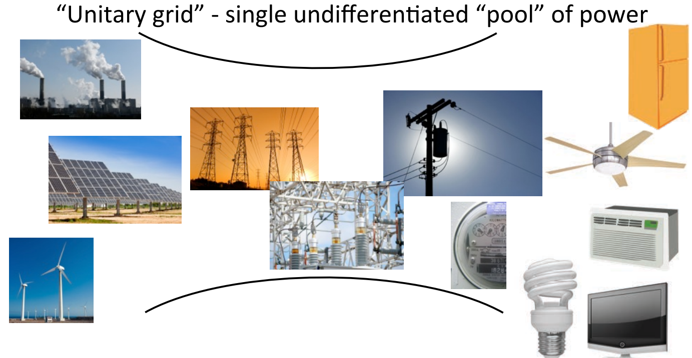
133 … 84 years later

Generation End use Distribution

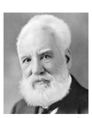


Traditional power distribution

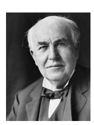
“Unitary grid” - single undifferentiated “pool” of power



- Buildings and all devices part of the pool



Communications and Power



- Phone system and utility grid invented about same time
  - Synchronous – highly coupled
  - Unitary – to end points – centrally managed
  - Organizations conservative - regulated
  - Technology advances slowly
  - Local variations in technology
  - One mode of operation

Paradigms

Old phone system	**Internet**
Utility grid	**Network model of power**
19^{th} century	$20^{th}/21^{st}$ century
Centralized	Distributed
Analog	Digital
No storage	Storage widespread
Tightly coupled	Loosely coupled
Entangled technology	Isolated technologies
Custom / Expensive	Commodity / Cheap
…..	…..

Need paradigm shift

Power & information distribution

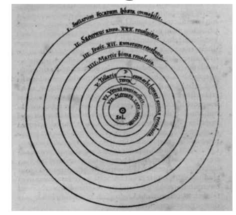
“Technology / infrastructure that moves data / electrons from devices where they are available to devices where they are wanted”

All bits/packets different; all electrons same

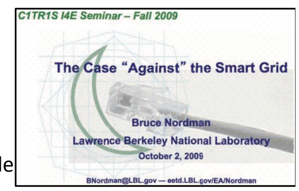
- Communications: understand system topology and move data accordingly
  - Data routing is how bits know where to go
- Grids: balance supply and demand
  - Price is how electrons know where to go
  - Routing power makes no sense

Location, quantity, timing

Paradigm changes

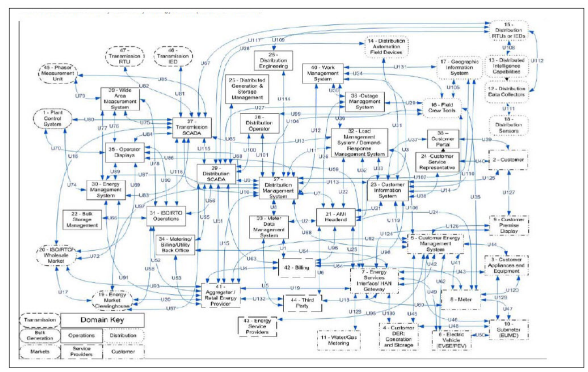



Some problems with “Smart Grid”



- Puts ‘digital veneer’ on 19th century grid model
- Places grid at center
- Tries to innovate by ‘scaling down’ technology
  - Microgrids treated as small-scale utility grids
- Expensive in development, design, equipment - slow
- Adds “band-aids” – not address fundamental problems
  - e.g. demand response vs dynamic pricing
- Technology designed around business model
- **Lacks coherent layered model**

Smart Grid – architecture run amok

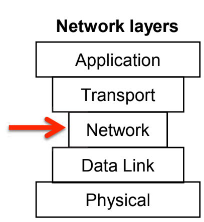


Source: NIST

Indications for network model of power

- Use digital technology everywhere
- Use storage to decouple/desynchronize
  - Distribute widely for stability, reliability
- Diverge technology in buildings from backbone technology
- Experiment with both shared media and P2P links
- Build end-use devices with multiple physical layers
- SIMPLICITY – $\boxed{\text{complexity}}$

Layered models



Interface at Meter
- Prices down
- Electrons either direction

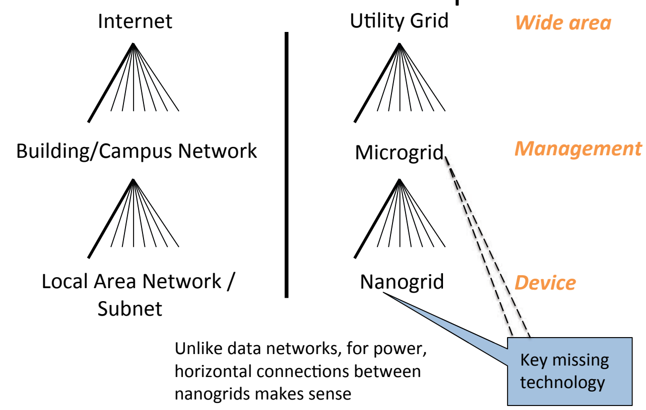
- Narrow waist in layering **isolates complexity** – facilitates interoperability
  - Buildings need three layered models
- Conventional network communication
  - Application and physical layers
- Electricity / utility meter
  - Utility grid from building
- Device internal Network Power Integration
  - Power distribution from functional control

Layered model for device operation for Local Power Distribution

Network Power Integration

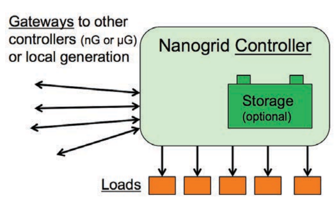
Network layers	NPI layers
Application	5. Functional coordination
Transport	4. Device discovery and events
Network	3. Internal integration — [Price / Quantity
Data Link	2. Exchange within/between grids
Physical	1. Transport of electrons

Scaling structure — communications and power

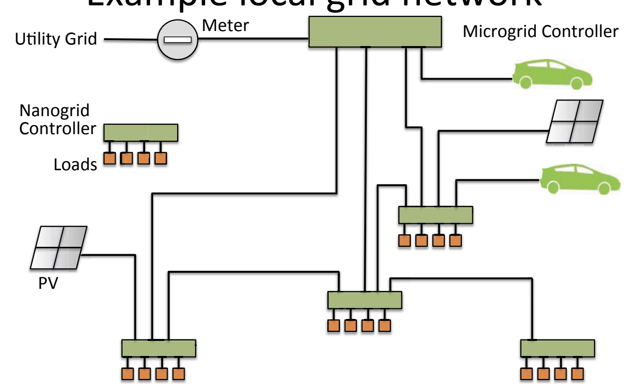


What is a Nanogrid?

- Smallest unit of power distribution
- Single physical layer (voltage; usually DC)
- Single domain: administration, reliability, capacity, and **price**
- Can interoperate with other local grids through gateways
  - Generation forms own nanogrid
  - Only two device types: grid controller and load
- In fully-functioning nanogrid, all links include communications
- Wide range in technology, capability, capacity

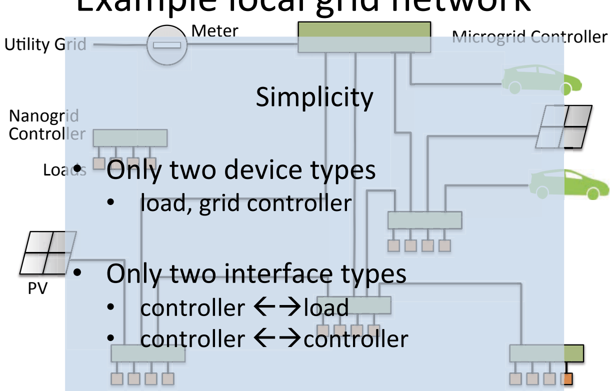


Example local grid network



All connections peer-to-peer and can be changed dynamically
Price is how devices know which way power should flow

Example local grid network

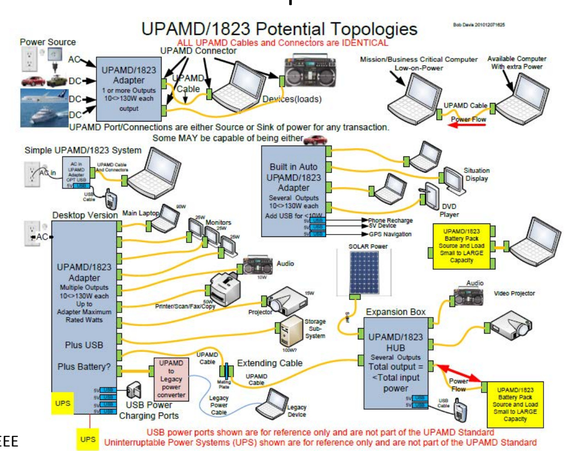


Simplicity

- Only two device types
  - load, grid controller
- Only two interface types
  - controller ←→ load
  - controller ←→ controller

All connections peer-to-peer and can be changed dynamically
Price is how devices know which way power should flow

IEEE - Universal Power Adapter for Mobile Devices



Source: IEEE

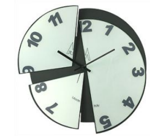
Features we should demand for power distribution

- "Plug-and-play" operation
  - End-use devices
  - Local generation
  - Local storage
- Arbitrary power topologies – inter-building links
- Improved safety
- Fine-grained management of constrained supply
- Enabling optimal operation with a local price
- Greater efficiency with Direct DC
- Greater reliability – and lesser
- Universal technologies
- Security / privacy

LPD provides these features

Myth of uniform power availability

- Electricity is <u>not</u> equally available across space and time
  - Has long been true within utility grid
    - "Locational Marginal Price"
  - Increasingly true within buildings
    - Local storage and/or generation, islanded grids, capacity constraints, combined heat-and-power, vehicles/mobile
- Technology we have today presumes uniform availability – **hence constant price**
- Dynamic pricing at meter a needed starting point
  - Grid can express preferences to customer

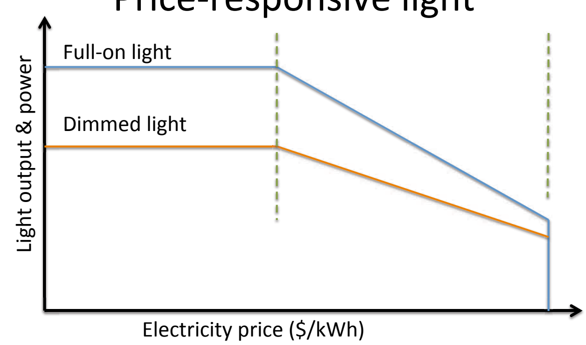


Reasons for differing local prices

- Differential buy/sell prices from utility
- Local valuation of carbon
- Losses from AC/DC or voltage conversion, battery losses, wiring losses
- Capacity constraints
- Off-grid operation – incl. mobile
- Battery management goals
- Local generation conditions (dispatch; co-gen)

- Price always **current** price and non-binding **forecast** of future prices

Price-responsive light

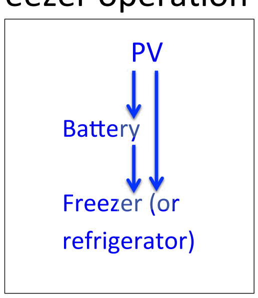


Control algorithms can change at any time

Local price to control freezer operation

- System components
  - Freezer or Refrigerator
  - PV Source
  - Battery

- 2 simulations
  - Constant price
  - Variable price



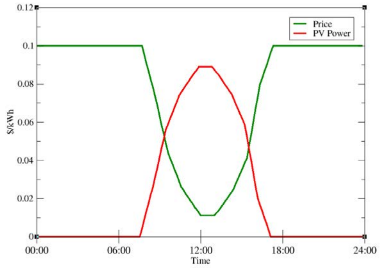
How the simulator works

PV output → Price/ Forecast → Device Setpoint → Device Behavior

- Process a series of steps
- Each step as simple as possible
- "Layered approach"
  - like Internet technology
- Complexity contained

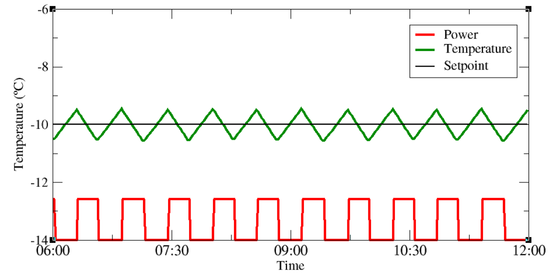
Creating a local price

- Context: stand-alone system of local photovoltaic (PV) power and a battery



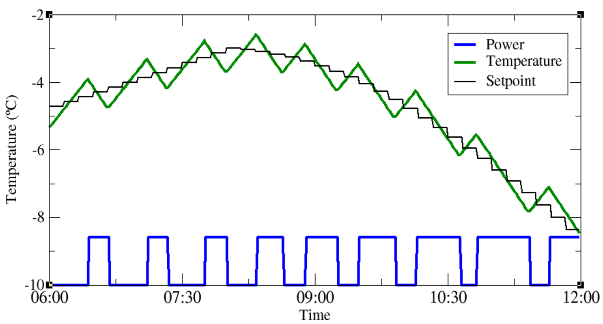
- The local price tracks power availability
  - lowest when PV output is highest

Freezer — Constant price



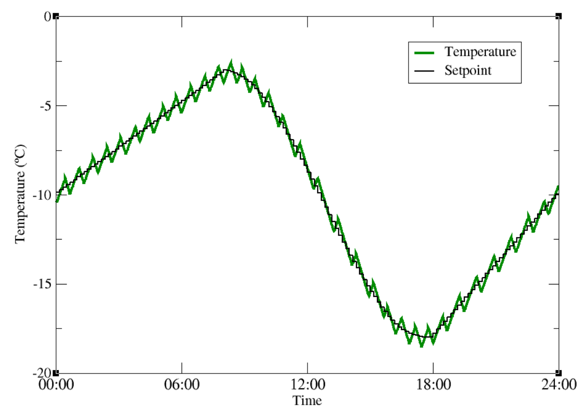
- Constant setpoint (-10 C)
- Compressor on-times and off-times about 20 minutes each
- Behavior never varies

Freezer — Variable price (6 hours)



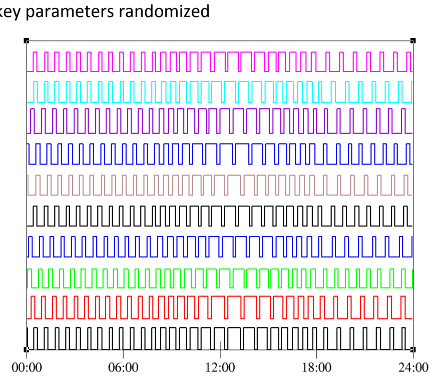
- Variable compressor on-times and off-times
  - (10 minute minimum on-times)

Freezer — Variable price (24 hours)



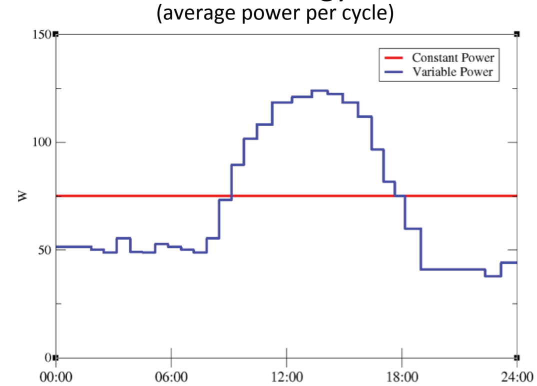
Multiple device results

- 10 Freezer (24 hours) - Power Consumption Distribution
  - key parameters randomized



Freezer energy use

(average power per cycle)



Local price results

- Less energy used overall
  - More direct DC
- Smaller battery
- Lower battery losses

- Model can be extended to arbitrary topologies of generation, storage, end-use devices

Communication about power

"Standard DC"

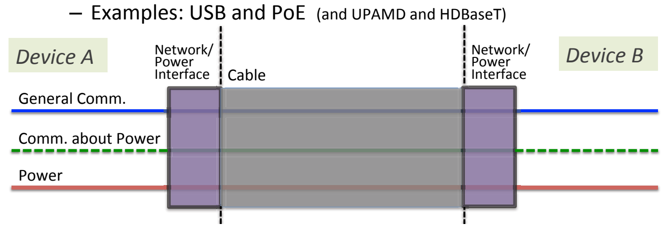
A method for transmitting DC power defined by a well-known technology standard, enabling plug-and-play interoperability

"Managed DC"

Standard DC technologies that include communications for managing power distribution within the power cable & connector

– Over the power wires or over adjacent wires

– Examples: USB and PoE (and UPAMD and HDBaseT)

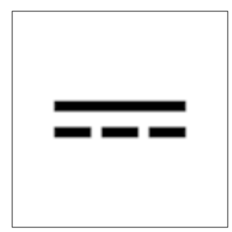


Steps to network model of power

- Simplicity
- Layered model
- Start at small scale – then scale up
- Scalable technologies (capacity; distance)
- Universal technologies
  – Geography, language, building type, people, time
- Don't design to legacy technologies
- Leverage innovation of IT/electronics sector
- Don't be shackled by cost, efficiency goals
- Differentiate local and backbone technology

Technology needs for LPD

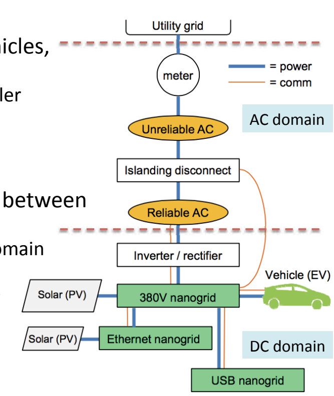
- USB and Ethernet have today*
  – Communications about power
  – 100 W per cable (HDBaseT; Ethernet advancing)
  – Bidirectional power (HDBaseT)
  – Power 'hubs' with integral storage
- USB and Ethernet need
  – Local price
  – Controller-controller links
- Need to consider for each
  – Multi-drop capability



**Ethernet itself not yet*

Proposed deployment path

- Use DC as integrator of local generation, local storage, vehicles, reliability
  – Storage integral to nG controller
  – Enables "Direct DC"
- Enable modest reliable AC
  – e.g. refrigerator
- Amount of power exchanged between DC, AC small
  – Most DC power stays in DC domain
- Can add DC capability incrementally and organically
- Can exchange power with neighboring buildings
  – Useful in disaster scenarios



Managed 380V DC

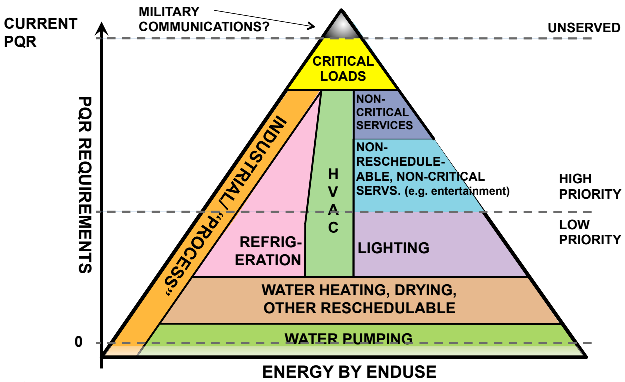
- 380V DC power currently lacks communications
- Inventing something new would be time-consuming and expensive

Proposal

- Have an Ethernet port adjacent to each 380V inlet and outlet
- String Cat-6 cable along each 380V cable
- Use Ethernet path to negotiate 380V characteristics ***before*** energizing power line
- Use Ethernet to power end device for communications in absence of 380V DC power
- Create local price with LPD
- Use Ethernet for general communication – or not

Differential PQR needs

(Power Quality and Reliability)



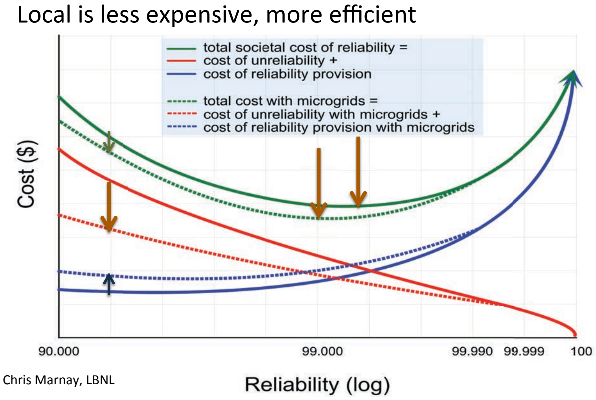
Source: Chris Marnay, LBNL

Hetergeneous PQR

- Traditional PQR is uniform, high (many countries)
  - Costs in $$ and efficiency
- Utility grid only capable of uniform PQR
- Even with advanced grids need higher PQR
  - Data centers, hospitals, industrial uses, emergency lights, phone systems, …
  - Residential: smoke detectors, timers, PCs, high-end audio/video, communications, …
- Utility grids always unreliable to some degree

Local reliability allows lower grid rel.

- Local is less expensive, more efficient



Source: Chris Marnay, LBNL

What does Internet tell us about quality and reliability? (QR)

- Mobile phones have lower QR
  - can obtain better when needed
- Network enables multiple services, e.g. video
- Technology basis is "best effort"
  - reliability guaranteed at edge of network
- Matching PQR delivered to needed
  - saves $, Energy, Carbon

Open Questions

- Shared media
  - Among end-use loads or among grid controllers
  - How valuable would they be? What complications would they add?
- Multi-drop ports for end-use loads
  - How valuable would they be? What complications would they add?
- Higher capacity link technologies
  - What should be created?
- AC power systems
  - What from LPD could be applied to?
-
-

Implications for U.S. grid

- If efficiency and local generation successful, easily
  - 50% less electricity use
  - 50% of remainder from local renewables
  - ➔Only 25% as many electrons across the grid as today
  - ➔System significantly over-capitalized – need to minimize new investment
- Local reliability investment more useful than central
  - Likely cheaper in long run
  - Need to **reduce** utility grid reliability goals (and quality)
    - Reduces vulnerability to cyberattack, physical attack

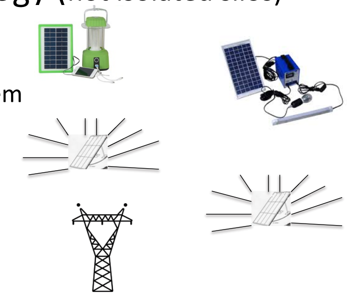
Implications for India grid

- Long-run capacity need likely lower than currently assumed
- Reliability goals can be moderated
- Emphasize local generation, reliability
- Charge higher, more dynamic, rates
- Provide differential PQR, pricing

- 100 W of reliable DC for each household a promising entry point for LPD

Energy Access -- Need continuum of technology (not isolated silos)

- Solar Lantern
- Solar Home System
- DC Mini-grid
- AC Mini-grid
- AC grid



All hardware should be useable in all grid contexts;
AC / DC, grid connection (always, never, intermittent);
size, complexity

Security / Privacy

- Unitary grid a disaster
  - Too many organizations, devices, protocols, …
  - Highly vulnerable; hard to fix
- Smart grid based on maximizing communication
- LPD minimizes communication
  - Including interface at meter

- Effective grid management does not require entangling grid and end-use devices

Summary and Next Steps

- Need network model of power
  - LPD is one – highly practical
- Nanogrids can be key to success of microgrids
  - Can be deployed faster, cheaper
- Key missing technologies: pricing and gateways
- Keep traditional grid, but make it *less* reliable

- Nanogrids are a “generally useful technology”
  - For all application contexts
  - Like Internet

Thank you